planet.

Joint Agency Commercial Imagery Evaluation
NASA • NGA • NOAA • USDA • USGS
JACIE

Long Term Geometric Stability of the SkySat Constellation

Dr. Byron Smiley, 19 Sep 2018

Mercator Projection

outline

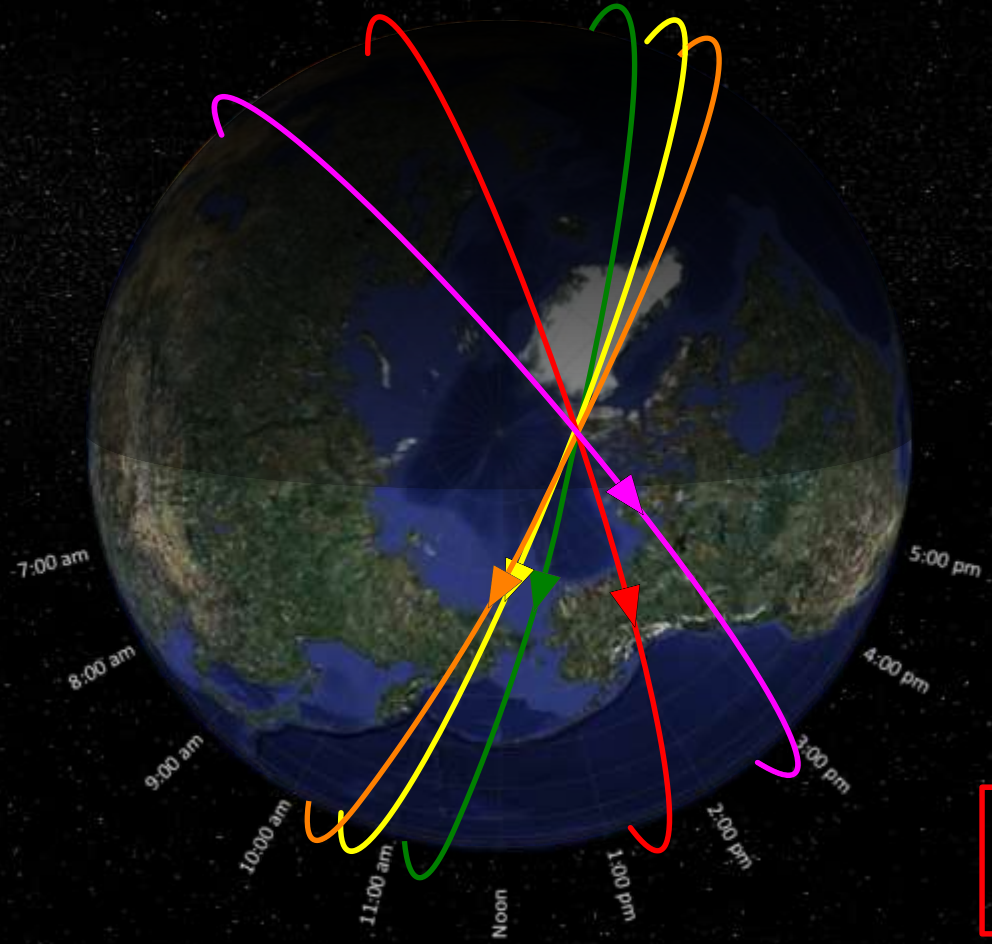
- constellation update
- high precision methods
  - description
  - results
- low precision methods
  - motivation
  - description
  - comparison to high precision results
  - current results

Khi Solar One, South Africa

SkySat constellation update

Iguazú National Park, Brazil – September 23, 2016

Planet has 13 SkySats, with 2 more coming

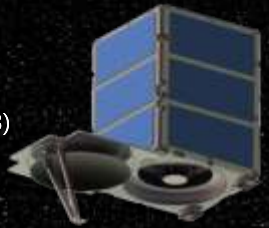


SkySat-1

- launched on Dnepr, 21 Nov 2013
- **~570 km, 11:03am** (as of Sep 2018)

SkySat-2

- launched on Soyuz, 8 Jul 2014
- **~620 km, 2:36pm** (as of Sep 2018)



"generation A"

SkySat-3

"generation C"

- launched on PSLV, 22 Jun 2016
- **~495 km, 10:34am** (as of Sep 2018)

SkySat-4 5 6 7 (Block 1)

- launched on Vega, 16 Sep 2016
- **~495 km, 10:15am** (as of Sep 2018)

SkySat-8 9 10 11 12 13 (Block 2)

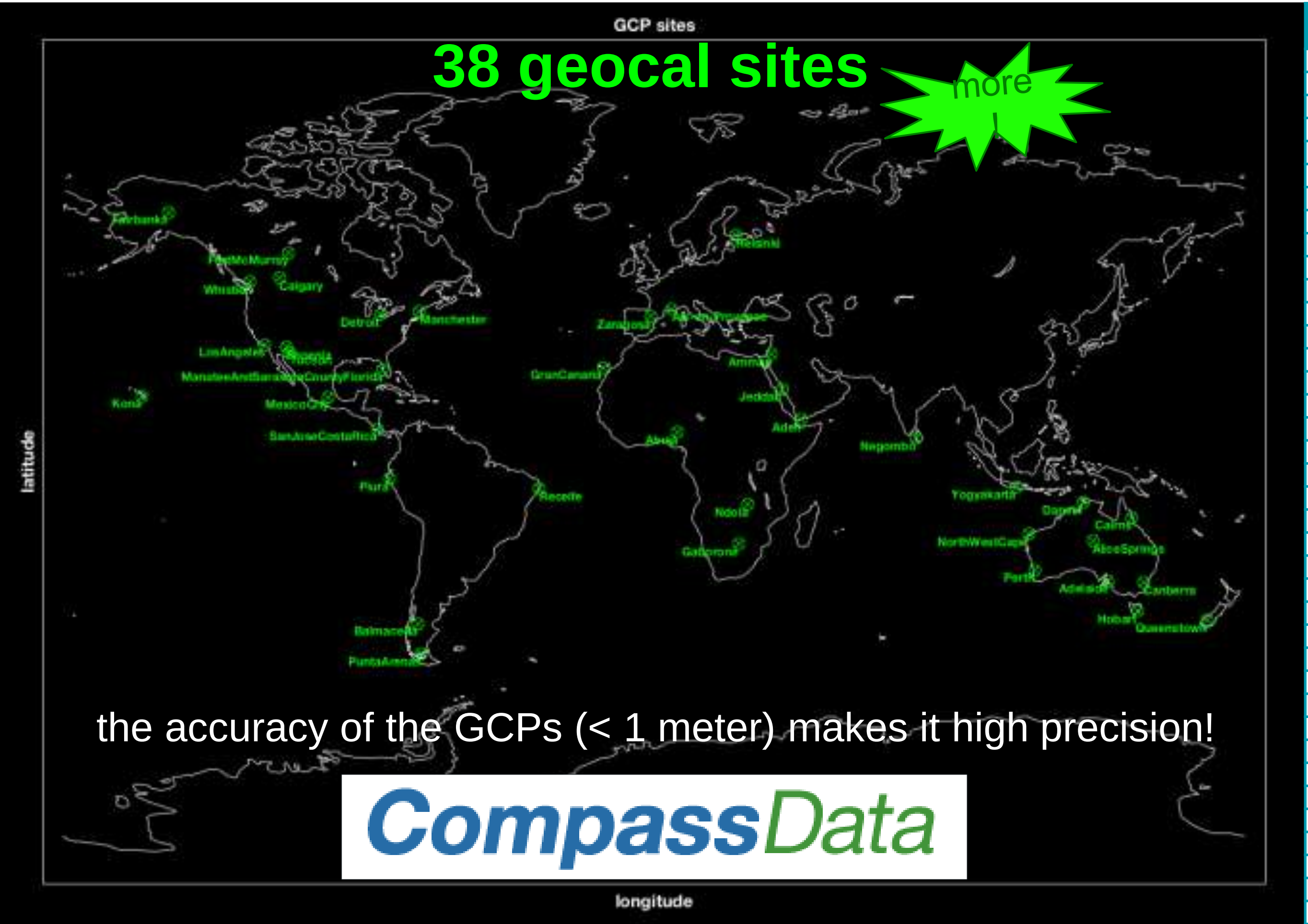
- launched on Minotaur, 31 Oct 2017
- **~500 km, 1:07pm** (as of Sep 2018)

SkySat-14 15 (remaining Block 2)

- expected launch on a SpaceX Falcon 9, mid-Nov 2018
- **~500 km, 1:00pm to match Block 2**


high precision methods
a very brief review
Lake Simcoe, Ontario, Canada – February 23, 2016

absolute geolocation accuracy is measured with GCPs



GCP sitename	# GCPs
Fairbanks, Alaska	11
Helsinki, Finland	10
Fort McMurray, Alberta	9
Calgary, Alberta	14
Whistler, British Columbia	5
Aix-en-Provence, France	8
Manchester, New Hampshire	4
Detroit, Michigan	7
Zaragoza, Spain	7
Los Angeles, California	13
Phoenix, Arizona	65
Tucson, Arizona	3
Amman, Jordan	8
Gran Canaria, Spain	5
Manatee & Sarasota County, Florida	7
Jeddah, Saudi Arabia	7
Kona, Hawaii	5
Mexico City, Mexico	13
Aden, Yemen	8
San Jose, Costa Rica	7
Abuja, Nigeria	5
Negombo, Sri Lanka	7
Piura, Peru	9
Yogyakarta, Java	9
Receife, Brazil	5
Darwin, Australia	4
Ndola, Zambia	5
Cairns, Australia	15
North West Cape, Australia	4
Alice Springs, Australia	24
Gaborone, Botswana	4
Perth, Australia	10
Adelaide, Australia	5
Canberra, Australia	10
Hobart, Tasmania	9
Queenstown, New Zealand	8
Balmaceda, Chile	8
Punta Arenas, Chile	8

GCPs are marked using a MATLAB codebase

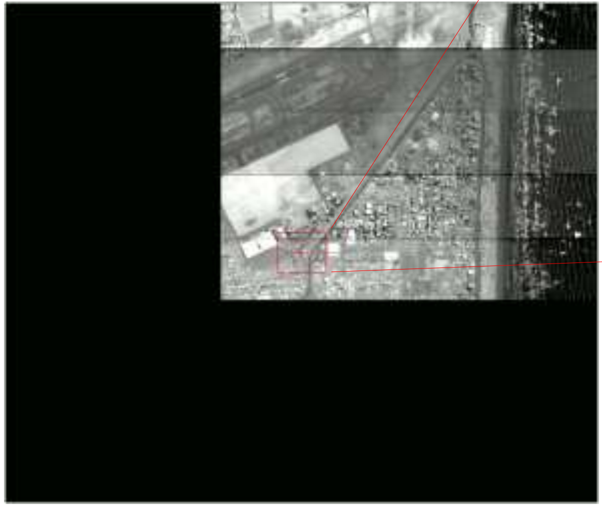
Aden GCP

YAA104

marked in **9** frames

(ground scan speed and frameRate determine this)

full resolution detector image



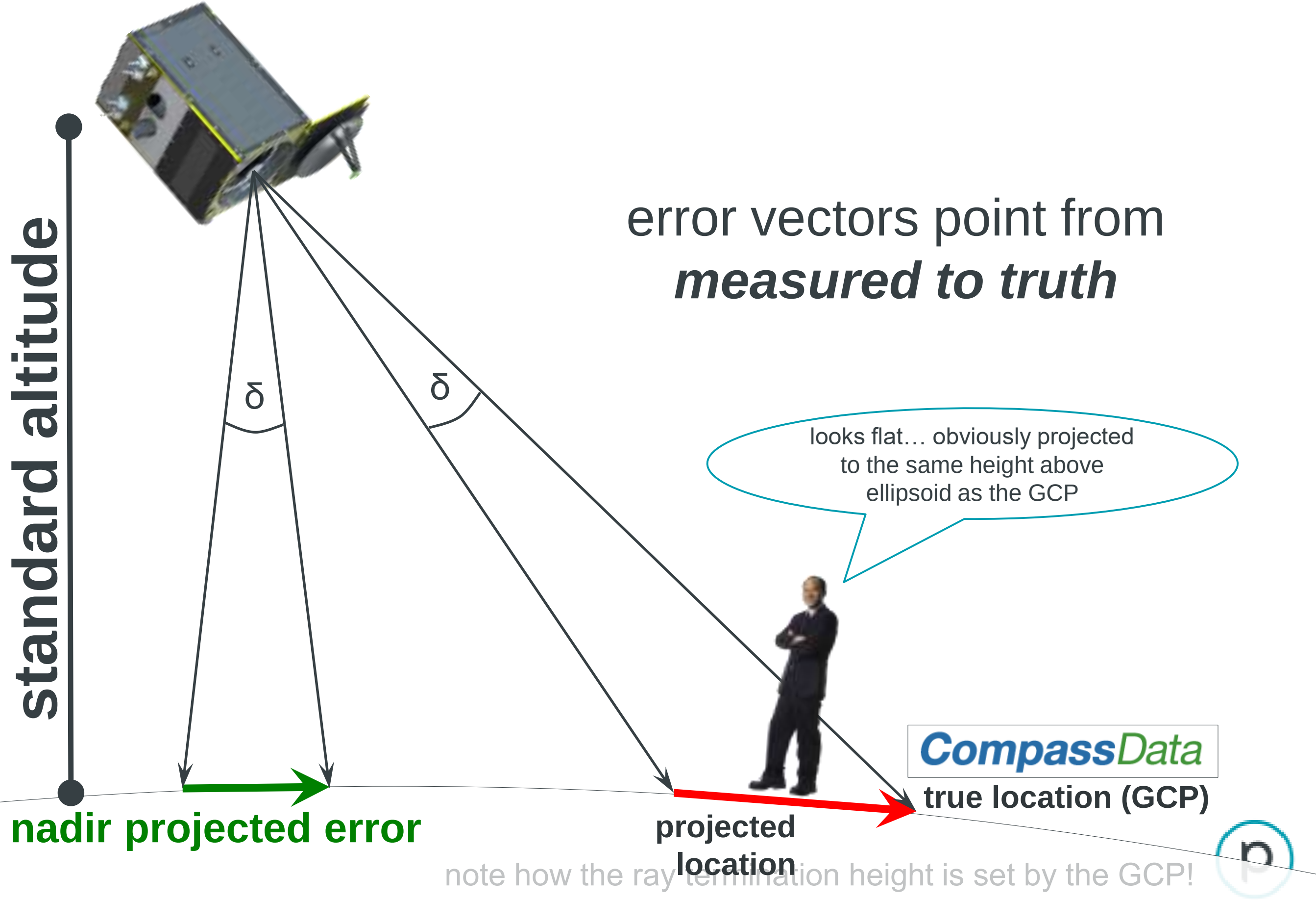
the accuracy of the marking (<1 pixel) makes it high precision!

geolocation errors are nadir projected during analysis

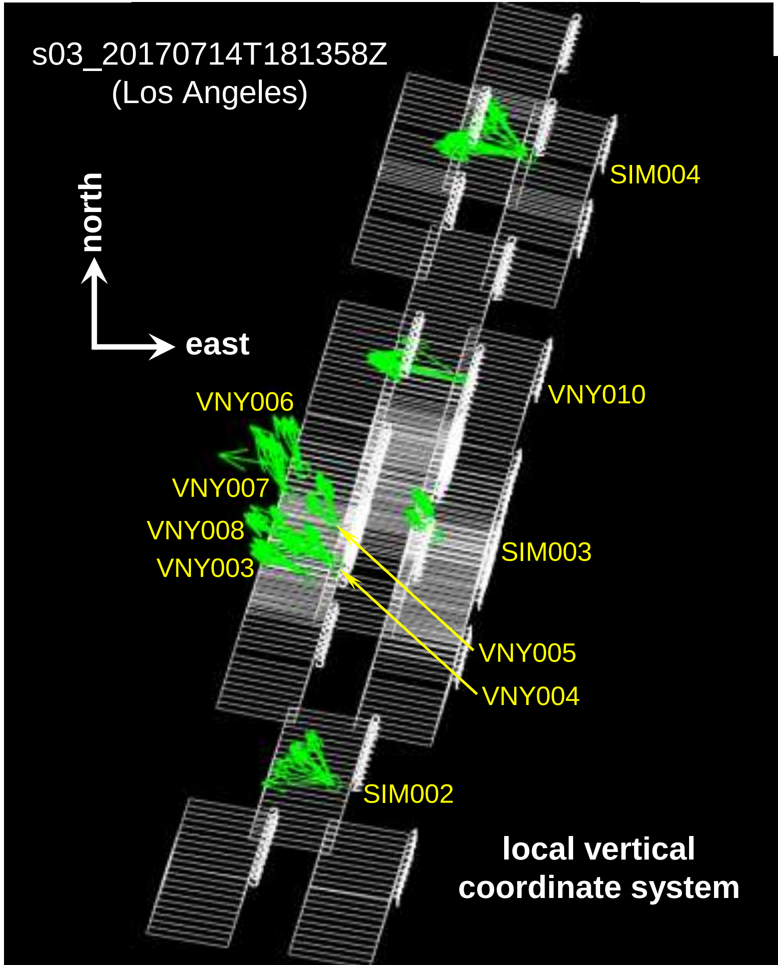
nadir projection is used to compare collects with different off nadir angles

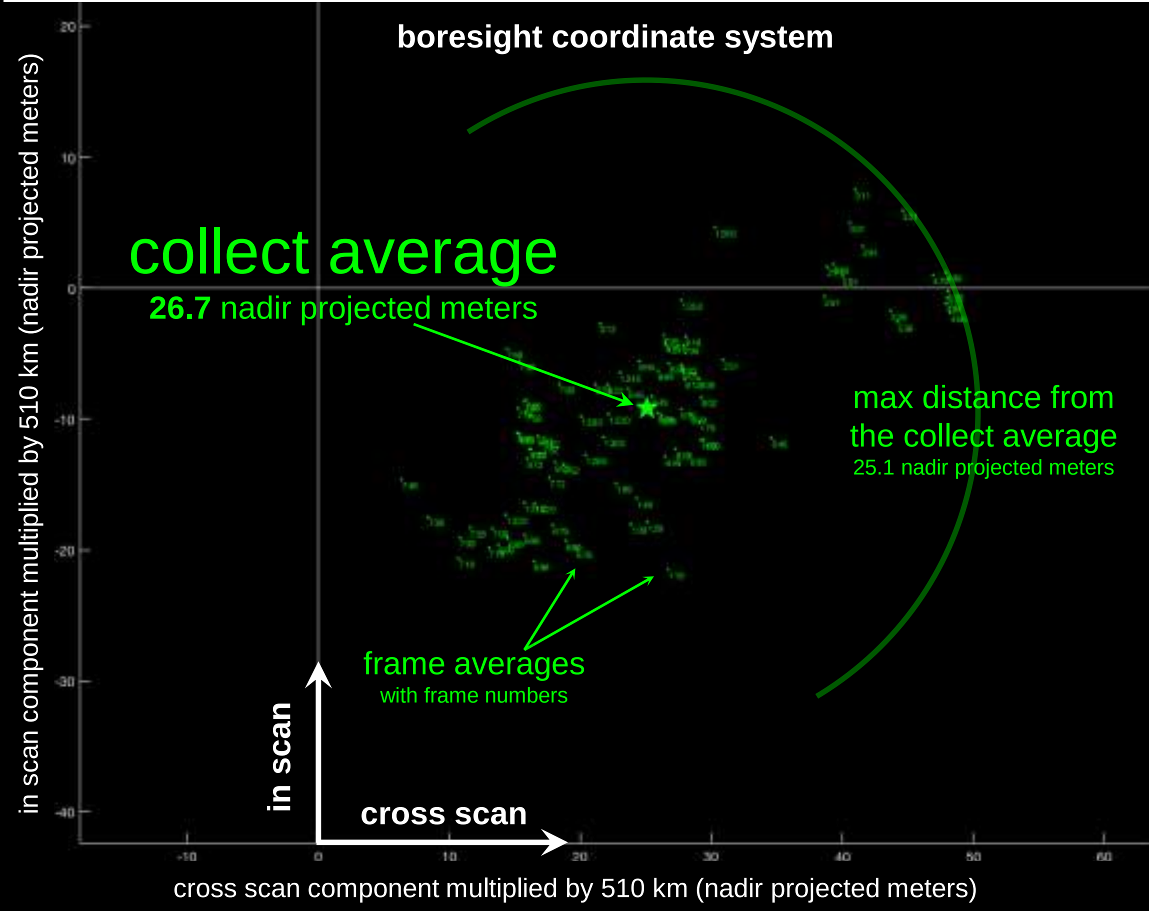
SkySat	standard altitude (km)
1	600
2	635
3…13	510

scaling factors **not** updated over time, to keep past results fixed



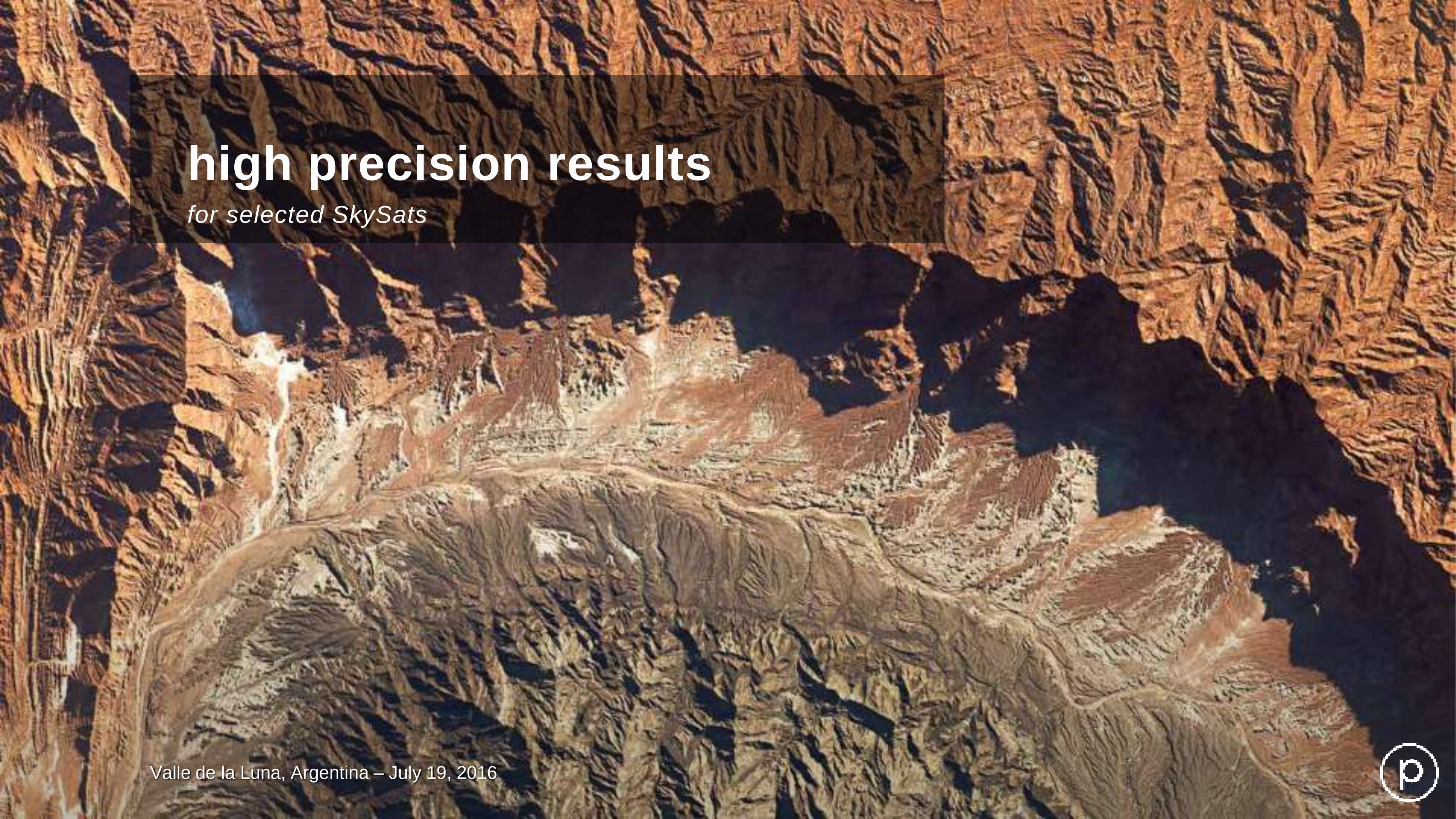
geolocation error changes as the frames roll in





high precision results

for selected SkySats



Valle de la Luna, Argentina – July 19, 2016

geometric stability is the norm

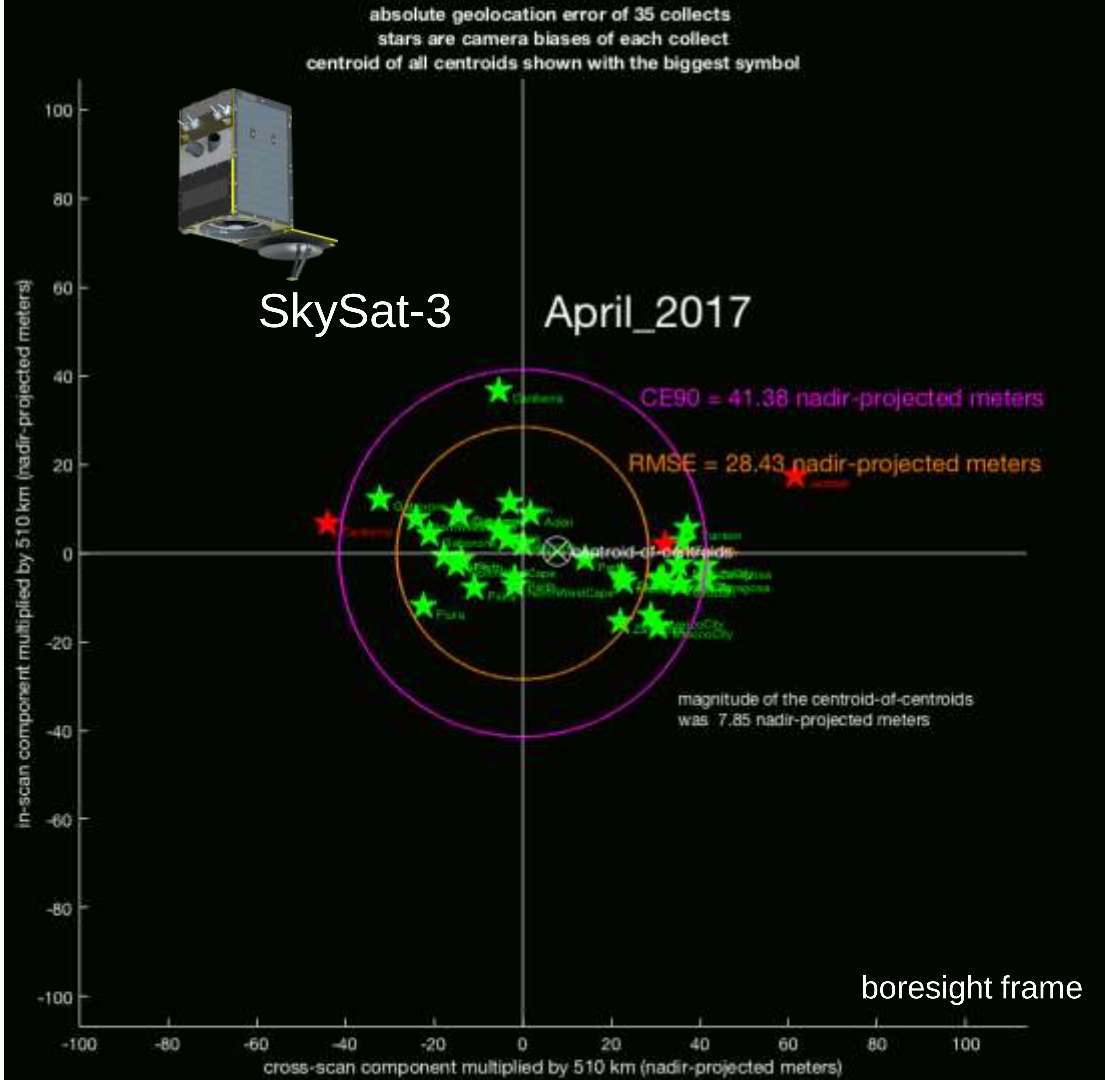
13 months of high precision monitoring reveal that C generation SkySats **are stable, rarely perturbed by anomalies**.

rarely = sometimes (!)

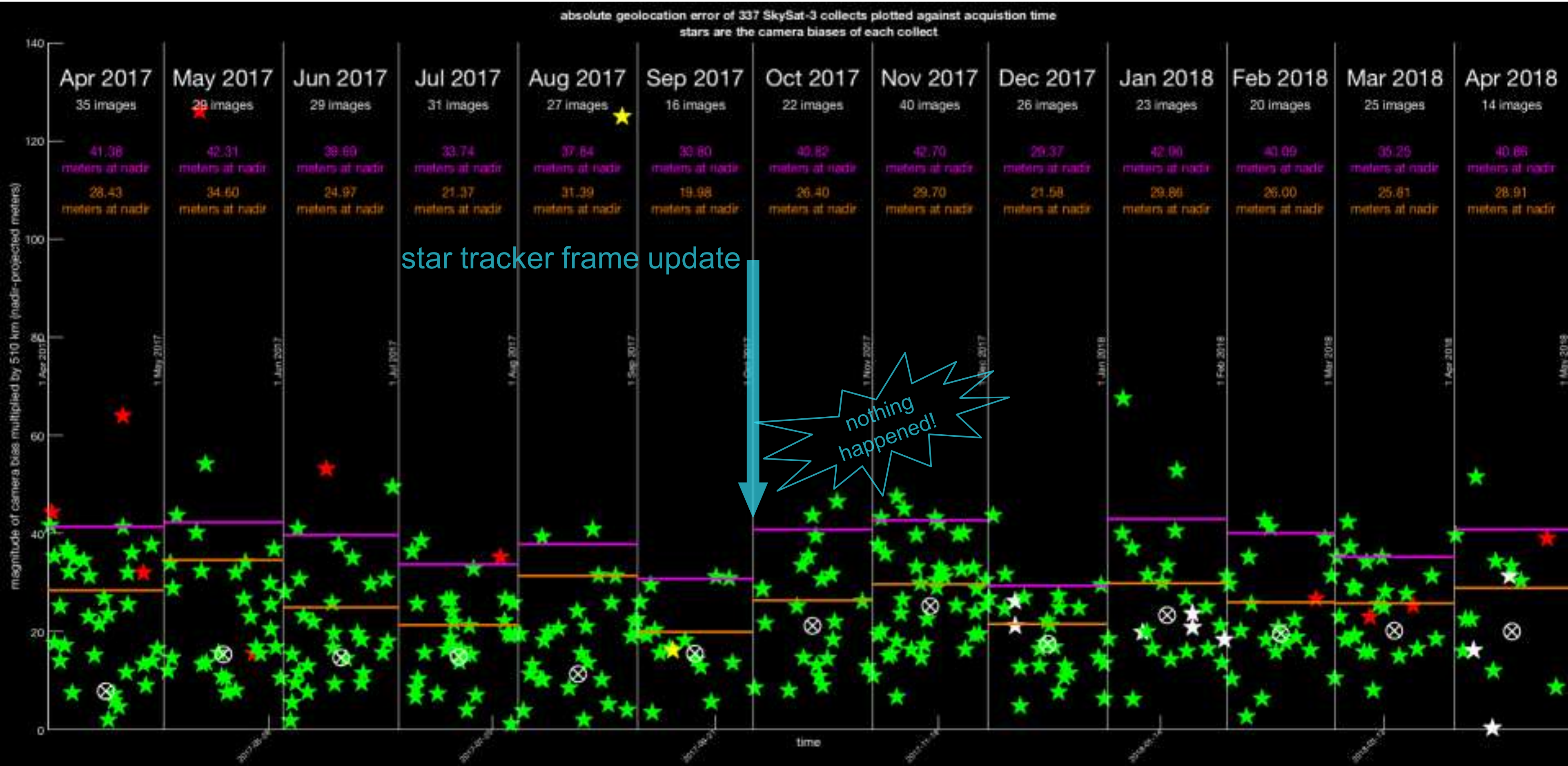
13 months of SkySat-3, ending in April 2018

collect average star color	meaning
white	tracker lock unknown
green	dual tracker lock
yellow	tracker A only
blue	tracker B only
red	“freaky”, “unsettled” (obvious Kalman filter problems)

13 months of good behavior!
no sudden increases in bias or CE90



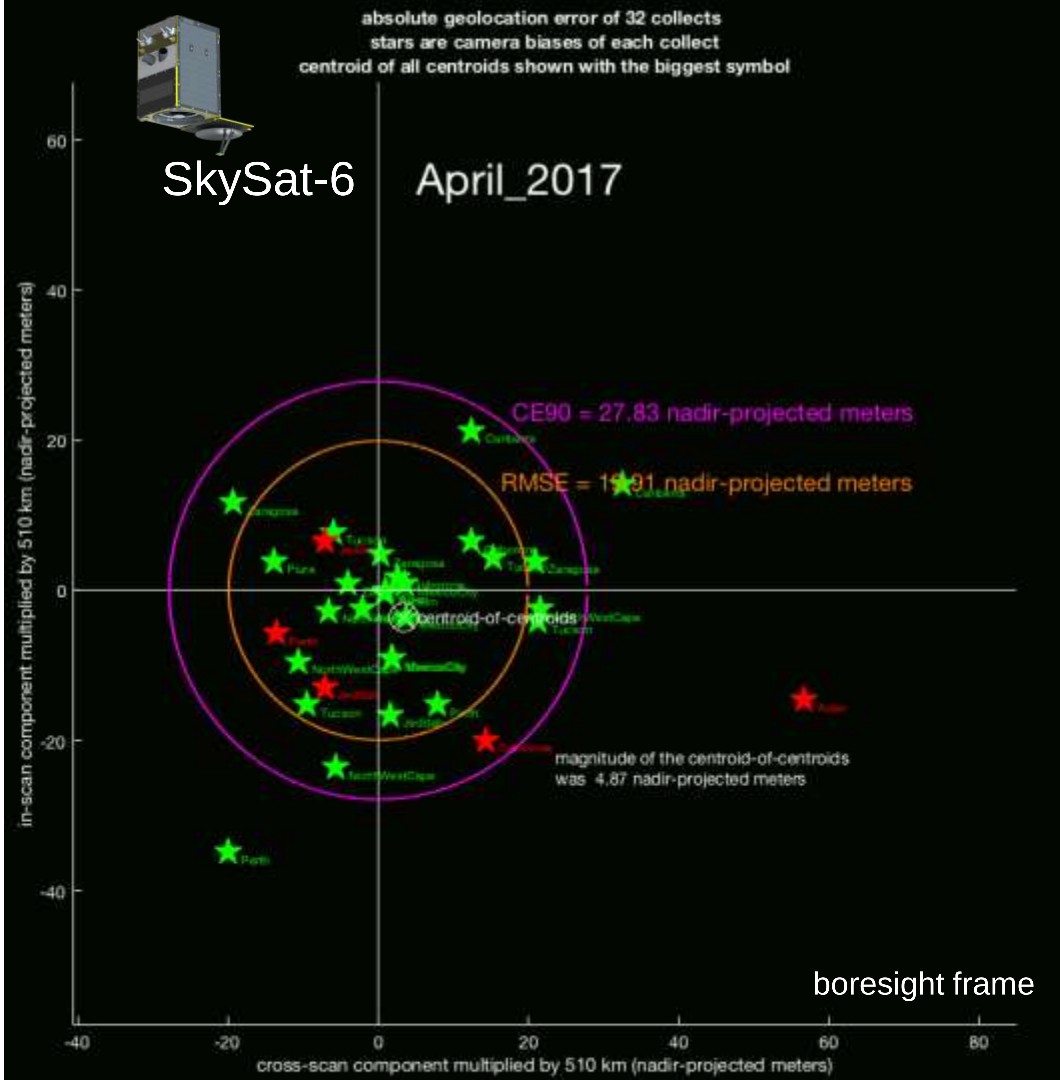
SkySat-3 was stable throughout the 13 month period



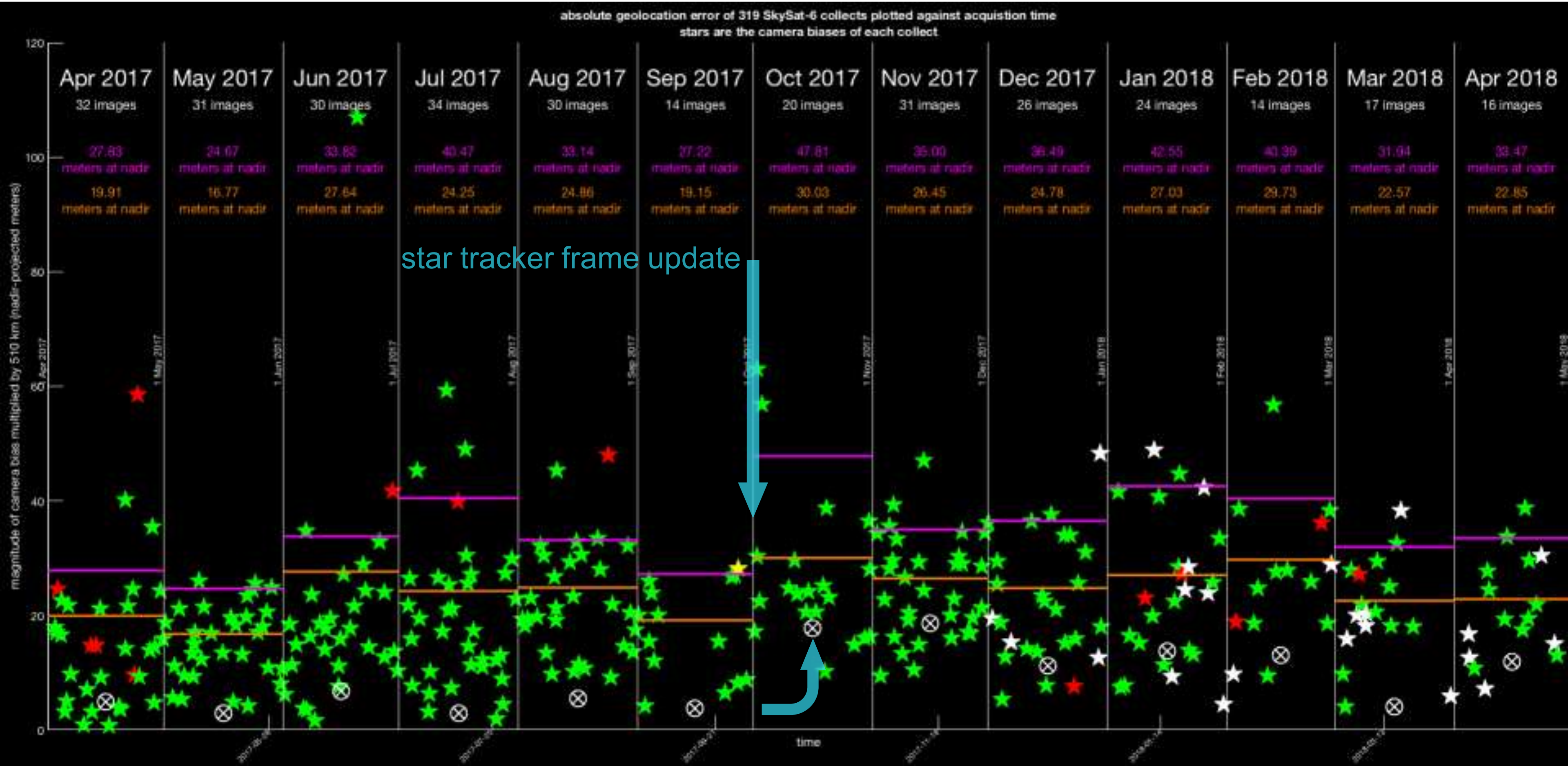
13 months of SkySat-6, ending in April 2018

collect average star color	meaning
white	tracker lock unknown
green	dual tracker lock
yellow	tracker A only
blue	tracker B only
red	"freaky", "unsettled" (obvious Kalman filter problems)

~18 meter bias appears in Oct 2017, after a star tracker frame update



SkySat-6 was stable except for a small bias appearing in Oct



low precision methods

Singapore Strait, Singapore – July 29, 2016

we can trade precision for automation

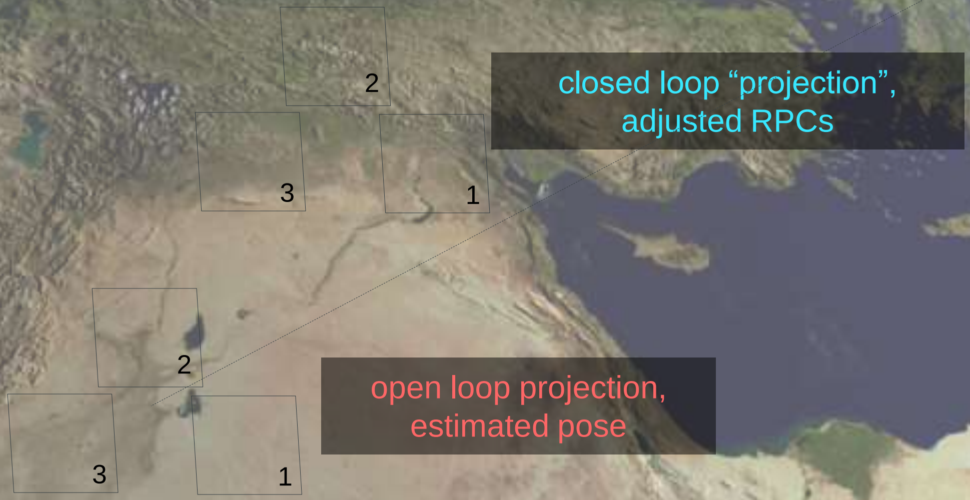
- high precision = requires Byron's time
  - (now with 13 satellites, that's **ALL** Byron's time!)
- given the geometric stability, this suggests we can downgrade to a **completely automated** alternative for routine monitoring
- adjustment performed by the production system fits the bill, but is **low precision**

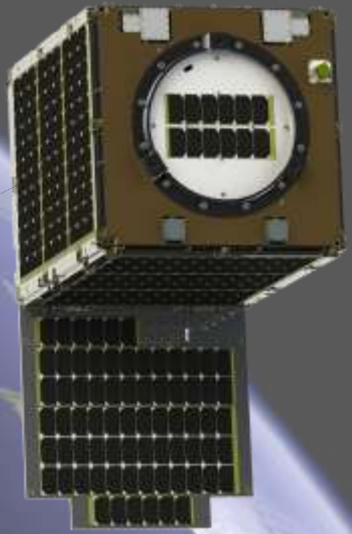
examine the delta between open and closed loop georeferencing

The Planet image processing pipeline adjusts imagery into alignment with the base layer, removing:

- up to 1 km of translation (roll, pitch)
- up to +/- 8° of yaw

and storing adjusted RPCs





* For more details, see my ASPRS 2018 presentation

the adjusted RPCs can be used as truth instead of GCPs

nadir projection is used to compare collects with different off nadir angles

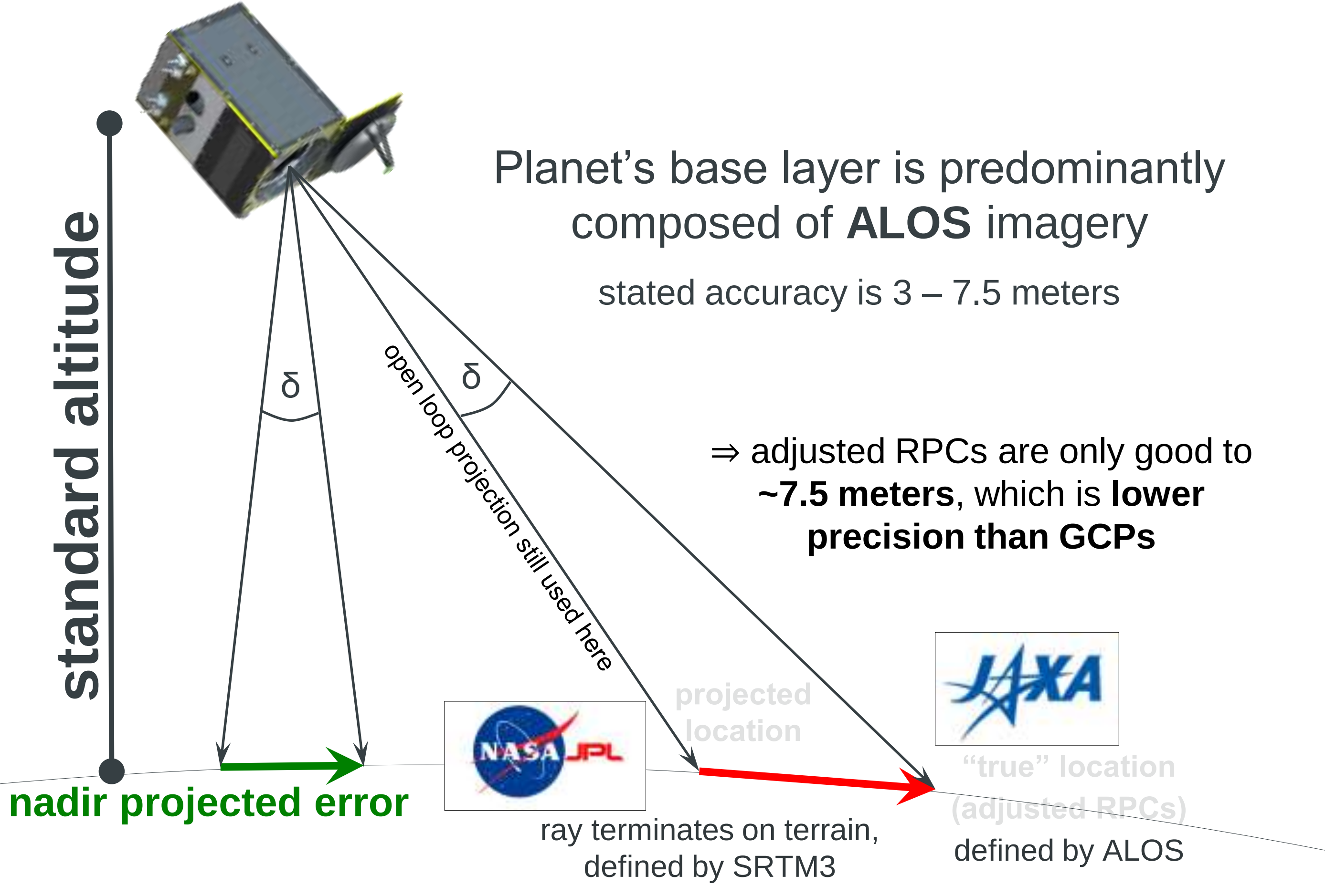
SkySat	standard altitude (km)
1	600
2	635
3…13	510

scaling factors **not** updated over time, to keep past results fixed

Planet's base layer is predominantly composed of **ALOS** imagery

stated accuracy is 3 – 7.5 meters

⇒ adjusted RPCs are only good to **~7.5 meters**, which is **lower precision than GCPs**



we can readily test low precision methods

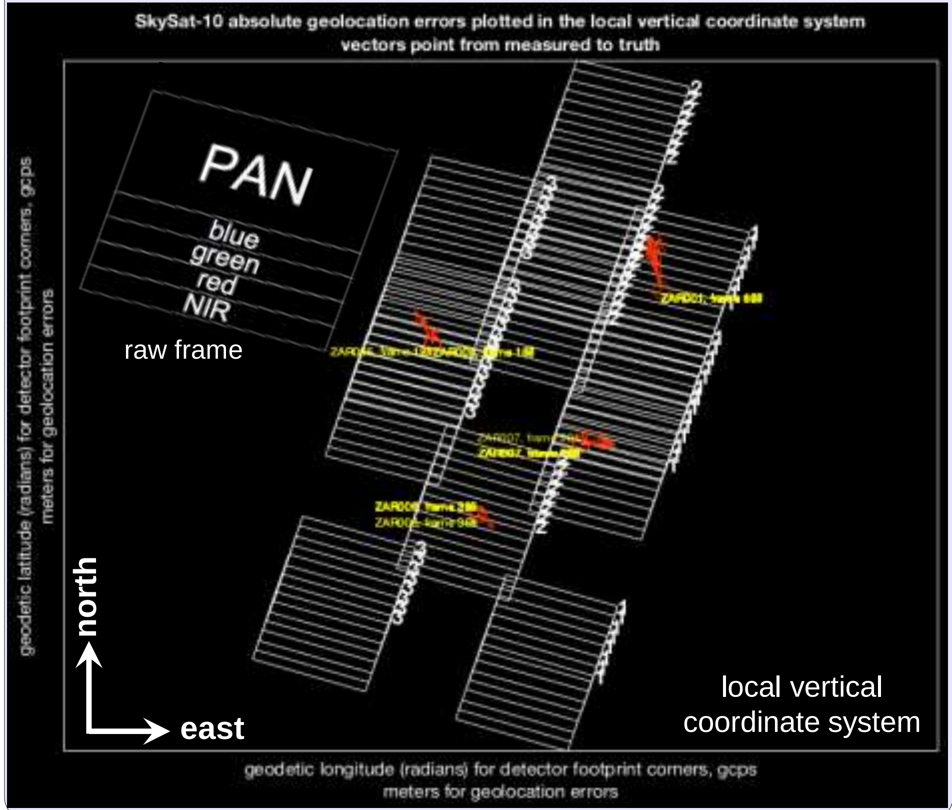
test if both high and low precision methods get the same geolocation error for a

single collect

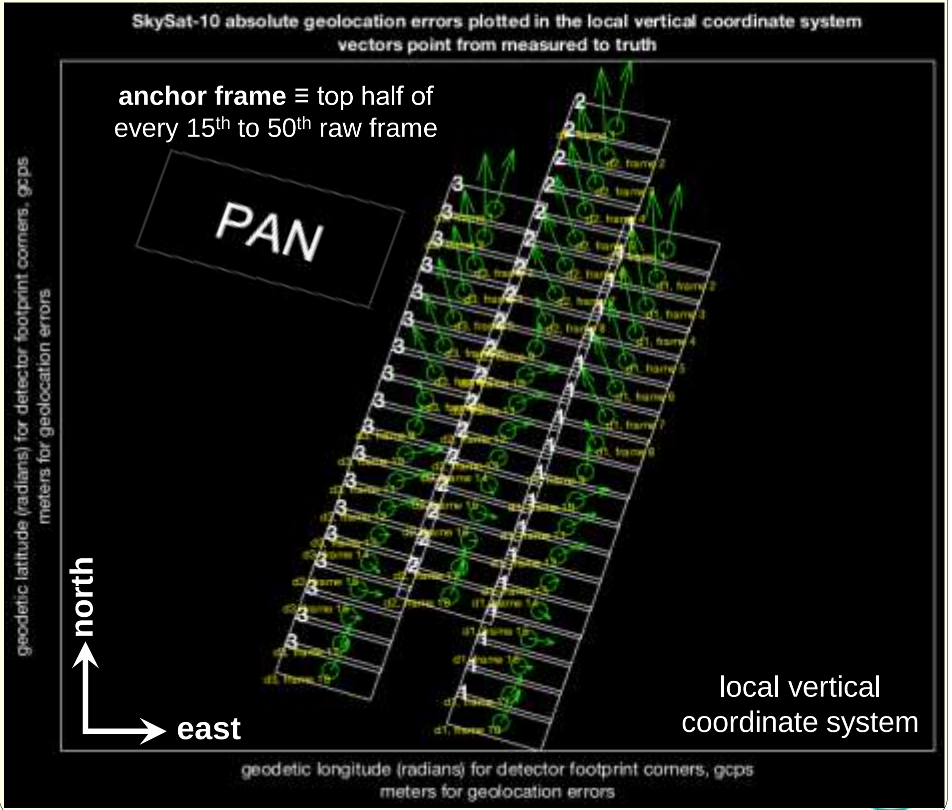
despite the differences, the results compare well

Zaragosa collect **s108_20180722T132530Z**

marked GCPs in raw frames (high precision)



using adjusted RPCs with anchor frames (low precision)



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Zaragosa collect **s108_20180722T132530Z**

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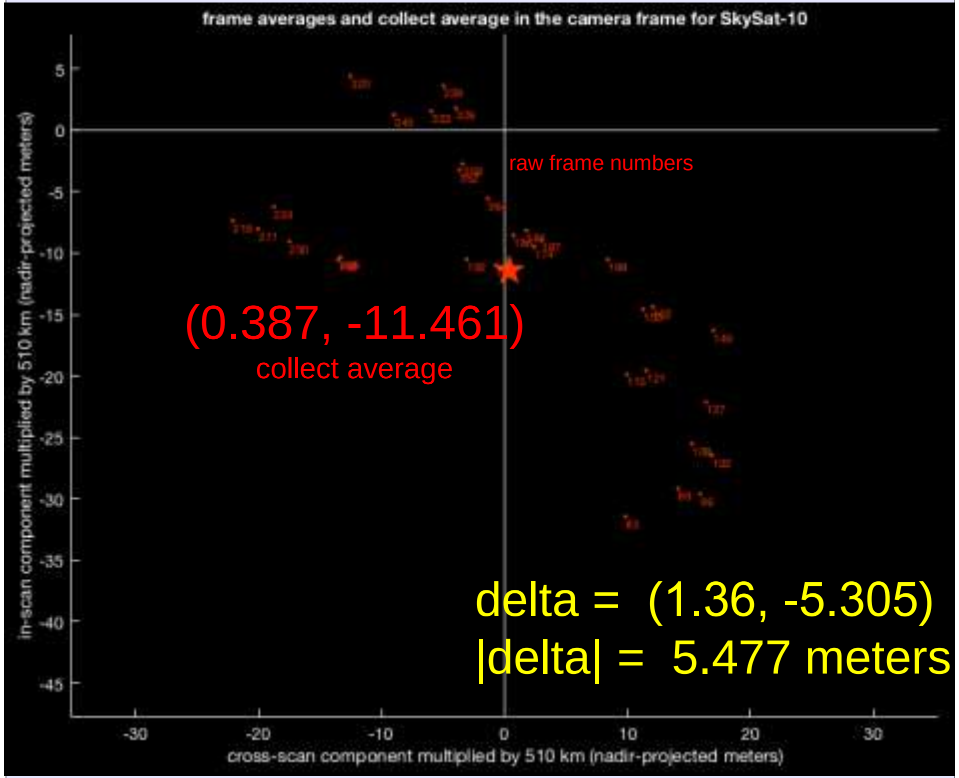
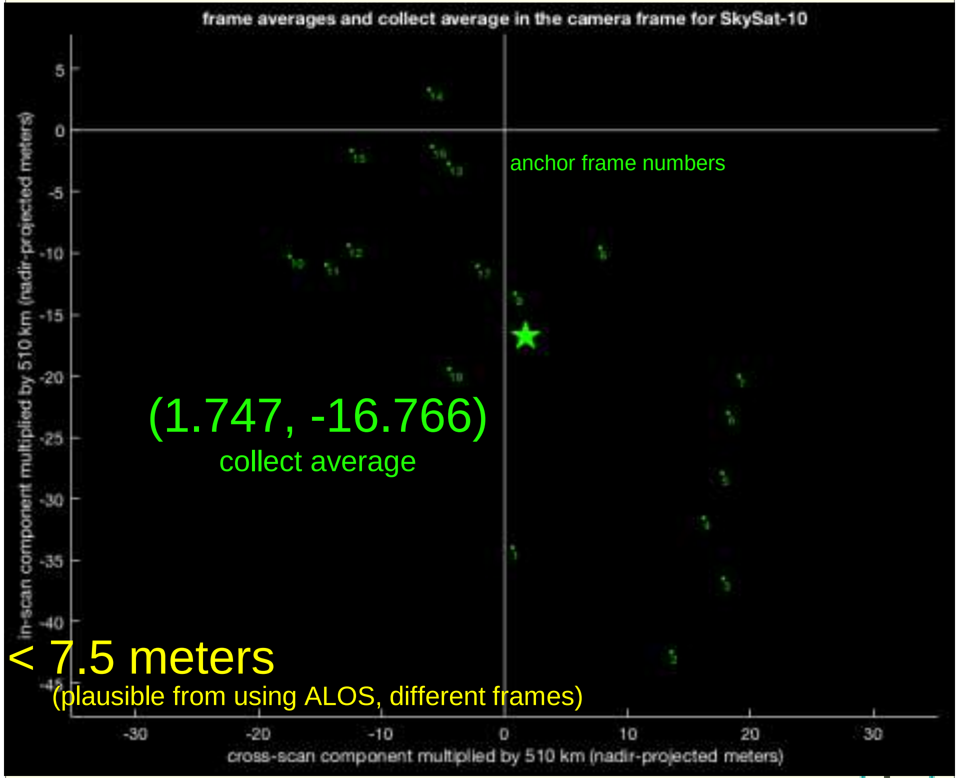


using adjusted RPCs with anchor frames (low precision)



we can readily test low precision methods

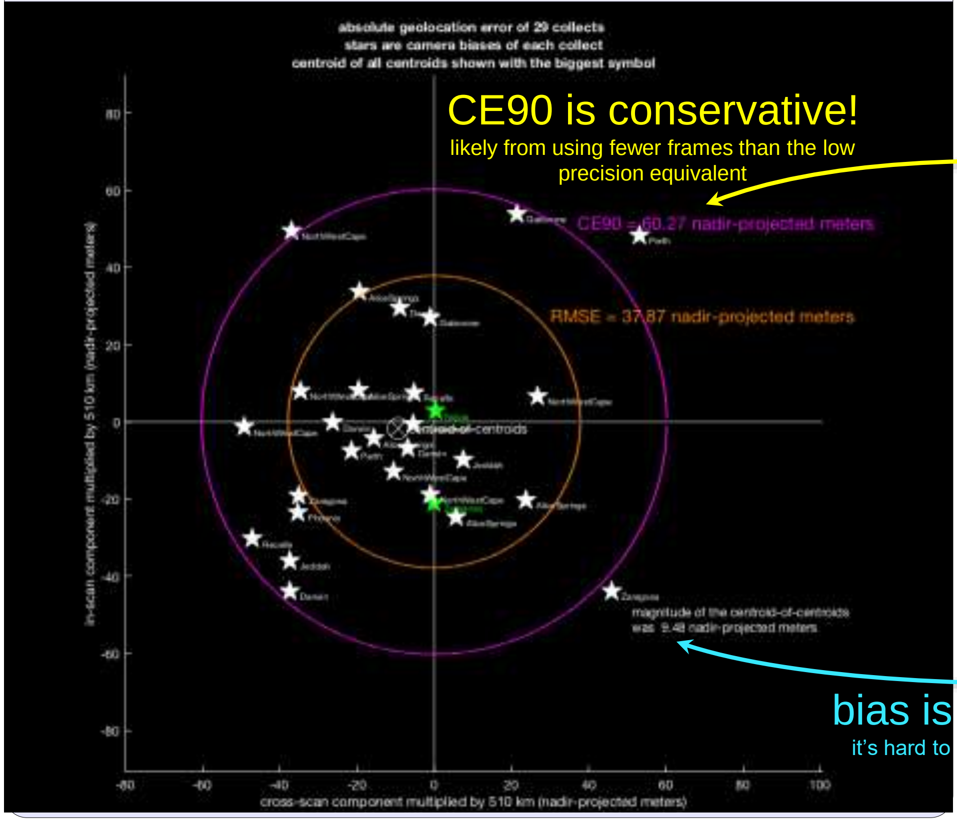
test if both high and low precision methods get the same geolocation error for a

single month

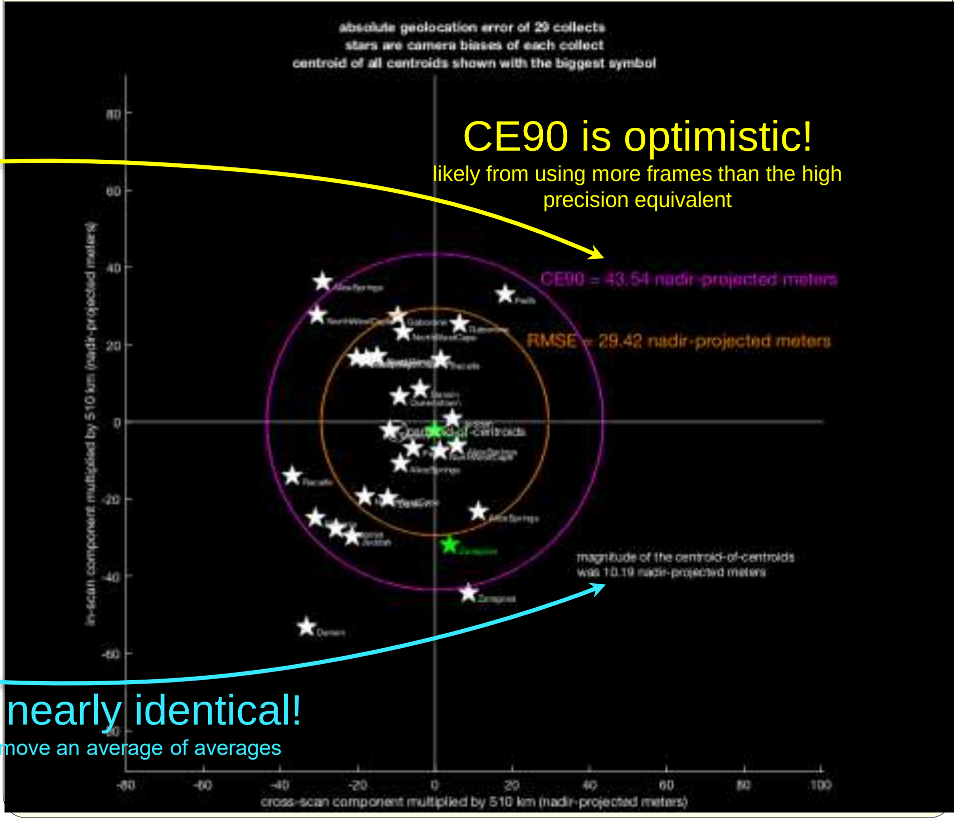
despite the differences, the results compare well

July for **SkySat-9**

marked GCPs in raw frames (high precision)



using adjusted RPCs with anchor frames (low precision)



bias is nearly identical!

it's hard to move an average of averages

Byron’s (new) official approach to geocal

- lowPrecision methods are a fast way to know which SkySats need help
- only SkySats in need require GCP methods
- note how **|bias|** is monitored, not **|CE90|**
- note how the threshold for intervention goes as 1% of the swathWidth:

SkySat	approximate swathWidth at nadir (km)	swathWidth*0.01 (m)
1	8.0	80
2	8.0	80
3…13	6.7	67

MATLAB

```
% loop over all SkySats
for SkySat = 1:13

    % have an initial look using low precision methods
    [ ce90 bias ] = lowPrecision_assess(SkySat, ‘Aug’, 2018);

    if (norm(bias) < swathWidth(SkySat)*0.01)

        % ignore well behaved SkySats
        continue

    end

    % have a closer look using GCPs
    [ ce90 bias ] = GCP_assess(SkySat, ‘Aug’, 2018);

    if (norm(bias) < swathWidth(SkySat)*0.01)

        % ignore well behaved SkySats
        continue

    end

    % deduce the boresight correction using GCPs
    q_betterBore2oldBore = GCP_correct(SkySat, ‘Aug’, 2018);

end
```

low precision results

London Array Wind Farm, United Kingdom – April 17, 2016

low precision methods can be leveraged immediately

monthly performance for selected Skysats,

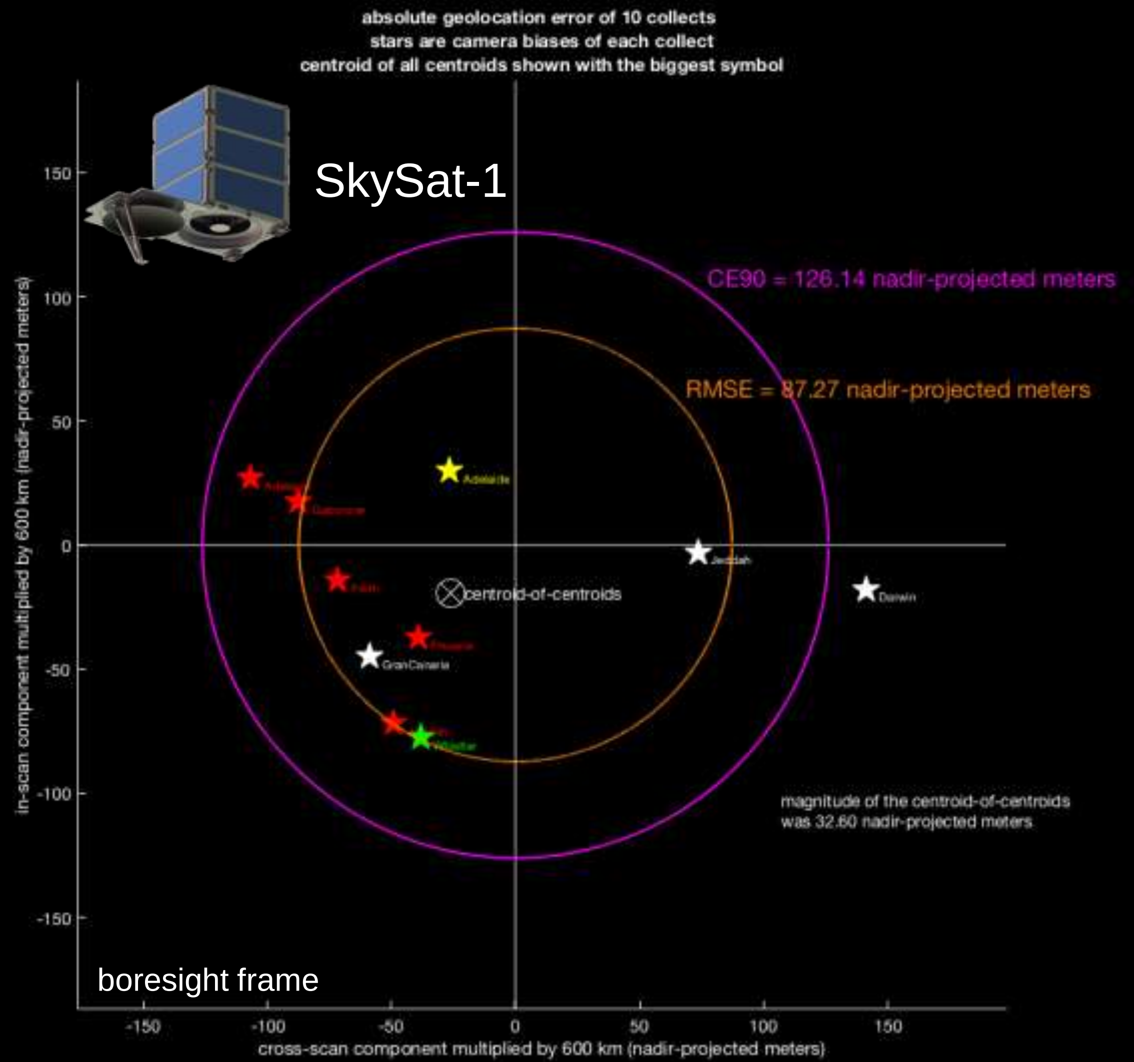
for last month (August 2018),

just because it's easy

SkySat-1, August 2018

collect average star color	meaning
white	tracker lock unknown
green	dual tracker lock
yellow	tracker A only
blue	tracker B only
red	“freaky”, “unsettled” (obvious Kalman filter problems)

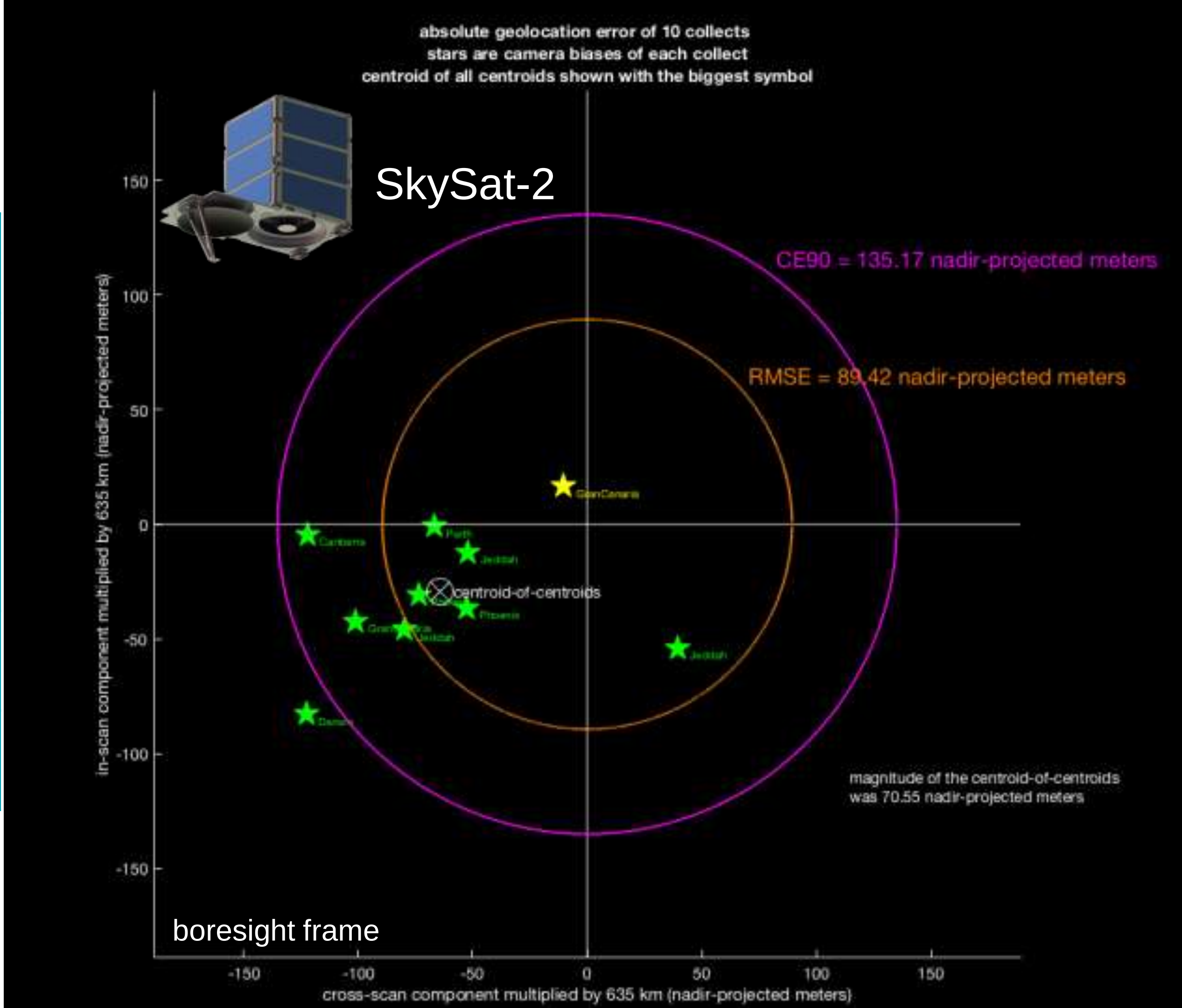
still hanging in there,
to this day…



SkySat-2, August 2018

collect average star color	meaning
white	tracker lock unknown
green	dual tracker lock
yellow	tracker A only
blue	tracker B only
red	“freaky”, “unsettled” (obvious Kalman filter problems)

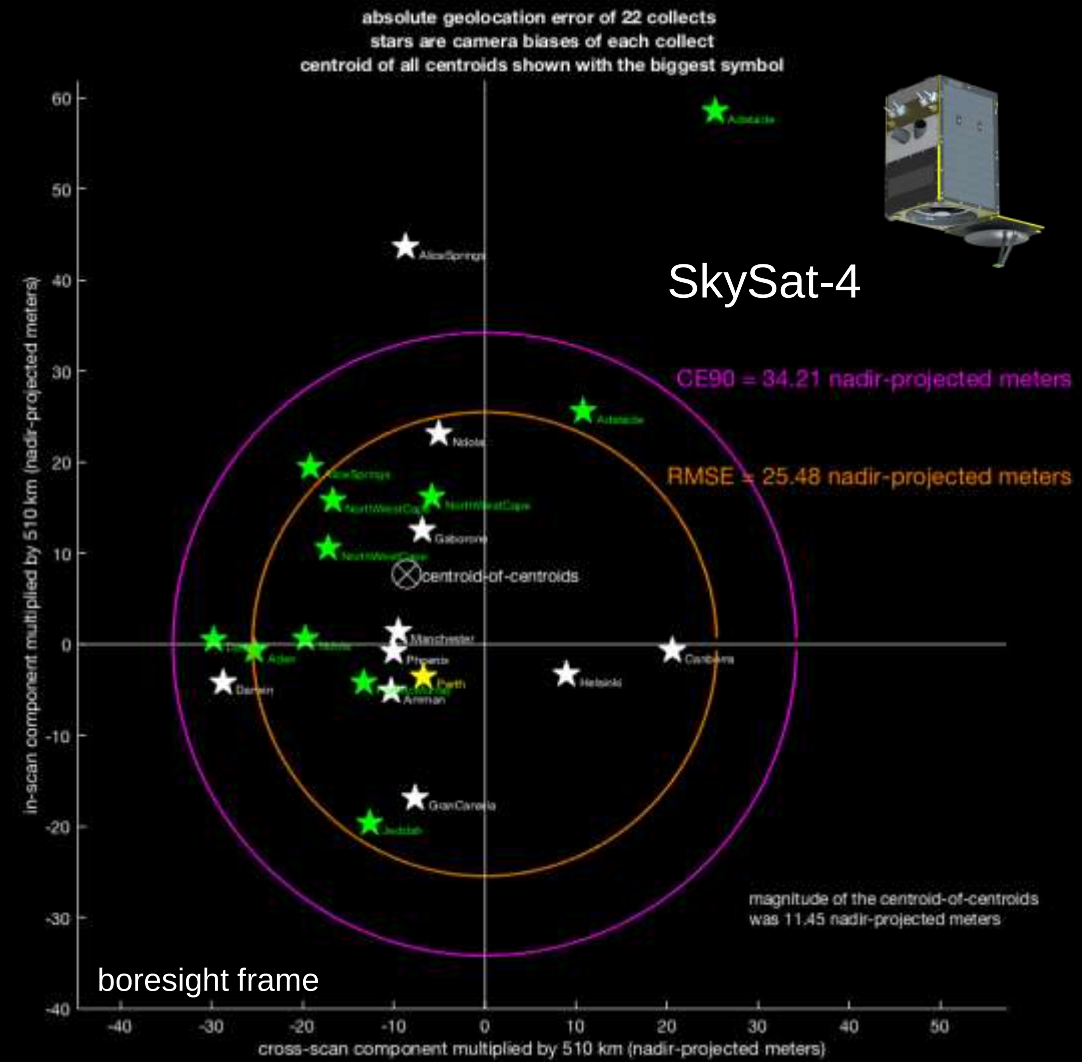
the bias is large enough to be significant, but tolerable



SkySat-4, August 2018

collect average star color	meaning
white	tracker lock unknown
green	dual tracker lock
yellow	tracker A only
blue	tracker B only
red	“freaky”, “unsettled” (obvious Kalman filter problems)

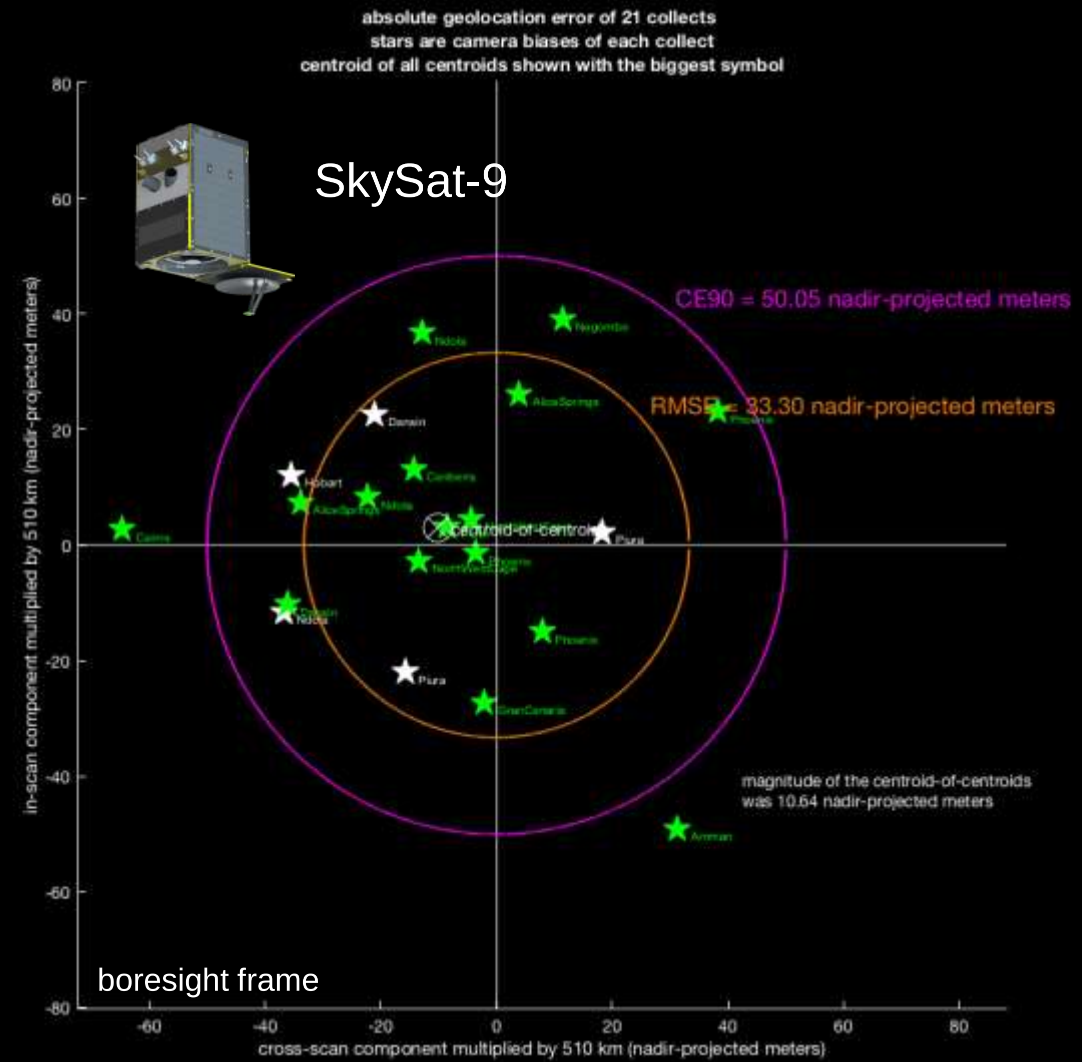
unbiased! No problems to fix!



SkySat-9, August 2018

collect average star color	meaning
white	tracker lock unknown
green	dual tracker lock
yellow	tracker A only
blue	tracker B only
red	"freaky", "unsettled" (obvious Kalman filter problems)

unbiased! No problems to fix!



conclusions

Great Barrier Reef, Australia – July 8, 2016

conclusions

- Planet’s SkySats are geometrically stable
- Planet has **high precision** methods for analyzing geolocation error
  - problems found and fixed with GCPs
- Now, Planet also has **low precision** methods for analyzing geolocation error
  - problems can be found faster than with GCPs*
  - problems are still fixed with GCPs (!)

* because Byron insists on 1 pixel marking accuracy

Khi Solar One, South Africa